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DEFINITION OF THE MARS ATMOSPHERE – A GOAL FOR THE EARLY MISSIONS

~~FIRST MISSION TO MARS – AN ALTERNATIVE VIEW~~

[redacted]

Carefully Designed Measurements of the Response During Entry of a Small Probe Vehicle Can Define the Mars Atmosphere For More Complicated Landing Vehicles to Follow

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Although it will clearly be a goal of the exploration of Mars to soft land instrument payloads on the surface, there is a very real question as to whether this should be the goal of the first probe to enter the atmosphere. The reason is that our best information on the properties of the Mars atmosphere indicates that the atmospheric densities are so low that the problem of slowing the vehicle to a survivable landing speed is a formidable one, and besides requiring extremely low vehicle densities, calls for the sequential use of large parachutes, impact attenuation devices, and perhaps retrorockets. Studies have shown that the payload fractions under these conditions are very small, from one to five percent of entry vehicle weight, to correspond to the least dense atmospheres now considered possible. Furthermore, the probability of success of the mission is unfavorably affected by the requirements for opening large parachutes or clusters of parachutes at high (perhaps supersonic) speeds, timing the firing of retrorockets, and selecting and controlling the impulse necessary to reduce touchdown speed to the required level, etc.

These considerations have indicated to the authors that the first goal of the Mars exploration program should be the reliable definition of the properties of the Mars atmosphere. While this will not necessarily remove the difficulty of the soft landing problem, it will at least present it in more definite terms. Conceivably, the properties of the atmosphere will be found to be appreciably different from those presently postulated, which are based on the most tenuous of data.

Recognition is also required of the important goal of the biologists on Mars, the search for extraterrestrial life. This requires that the probing of the atmosphere, which we hold to be not only beneficial but necessary to the later biological exploration, be done under sterile conditions which will not contaminate the planet with Earth life forms. This possibility is promoted by the use of small and simple atmospheric probing vehicles which can be sterilized by exposing them to the proper thermal cycle as whole units sealed in their sterilization envelopes.

Besides the benefits to the later physical and biological exploration of Mars, first unmanned and later manned, the measurement of the structure and composition of the Mars atmosphere holds much interest in its own right as a scientific experiment. It will be of interest to planetologists as a clue to the nature not only of Mars, but by its relation to Earth and the other planets, as a piece of information relating to the solar system and its origins.

A technique for measuring the properties of the atmospheres of the planets which is discussed and analyzed in reference 1 is the observation of the response of an entry vehicle to the atmosphere. This response can be sensed in many forms, in the deceleration, pitching oscillation, heating, and radiation exposure, to name a few, and the response can be analyzed to define the properties of the atmosphere encountered. The application of such a measurement technique to obtaining the properties of the Mars atmosphere has been studied at Ames Research Center continuously since the publication of reference 1, with the purpose of selecting the most promising experiments and determining the accuracy with which they could be made to yield the atmospheric properties. This article will describe some of the findings.

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The primary objective of the Mars atmospheric probe should be to define the profile of atmospheric density as a function of altitude, so as to guide the design of payload-landing vehicles to follow and also to provide a firm base for long range studies of manned entry systems, which decelerate on shallow entry paths at high altitudes. Integration of the density profile, once obtained, also permits the definition of static pressure profile, and the RT product profile, as noted in reference 1. Measurements of atmospheric temperature are also to be desired. This set of properties comprise what we shall call the atmospheric structure.

Other interest is attached to the atmospheric composition, which, while it is less critical than the atmospheric structure, can affect aerodynamics of some entry vehicle configurations (ref. 2) and the heating, particularly the radiative heating (ref. 3). Perhaps the greatest interest in composition however is the basic scientific interest, the desire to know more about the planet and its conditions. This pertains to both the physical science of the planet, and the possibilities for life, where the presence of certain chemical species in the atmosphere, such as water and simple organic compounds, can have determining influence on the origins and maintenance of life forms.

Atmospheric Structure Experiments.- The response of an entry vehicle to variations in the atmosphere it encounters is illustrated in figure 1. Large and clear differences in trajectory arise when either the scale height or the surface density is changed. The surface density determines the vertical position of the curve, and the scale height, its slope. Clearly, the measurement of the trajectory variables shown would provide an absolute distinction between the atmospheres used for examples in this illustration.

Rather than to analyze the data in terms of scale height, however, it is more direct and advantageous to determine the atmospheric density at a point on the trajectory from the measured instantaneous deceleration of the vehicle. From the classical defining equation of drag coefficient and Newton's second law of motion, we may write, as in reference 1

$$\rho = -2\frac{m}{C_D A}\frac{a_s}{V^2} \tag{1}$$

where a_s is the acceleration along the flight path. Given the value of $m/C_D A$ and V, the local density is determined, to the same percent accuracy as that with which the acceleration is measured. The velocity is known at entry from deep space tracking of the spacecraft in interplanetary flight. After entry, the velocity can be tracked by integrating the readings of the accelerometer,

$$V = V_E + \int_0^t a_s dt, \tag{2}$$

and the altitude can be obtained by integrating the vertical component of velocity.

$$h = \int_t^{t_{impact}} (V \sin \theta)dt \tag{3}$$

Error in the velocity, as given by equation (2), introduces errors into the density and altitude. These errors have been analyzed on the assumption that a bias error of a given fraction of the full scale range exists in the accelerometer. Bias errors are emphasized because they are more instrumental in causing error in the density and altitude than are random errors of the same magnitude. The latter tend to be averaged or cancelled out in the data smoothing.

Errors in the density resulting from various assumed bias errors in the accelerometer are shown as a function of velocity in figure 2. The error becomes small when the accelerometer bias is of the order of 0.1 percent of full scale--e.g., with 200 g full scale, errors of 0.2 g. Note that the density is then measured accurate within 2 percent down to about half the entry velocity, and within 5 percent down to 0.2 V_E. It is of interest that accelerometers meeting and exceeding this accuracy specification are commercially available from a number of manufacturers.

The larger errors which occur at the terminal part of the descent, below 0.2 V_E, are due to poor determination of the velocity when the velocity is small.* At small velocities however, particularly below sonic speed, it becomes possible to directly measure the ambient pressure and temperature. The remaining unknown for defining the low altitude density, the gas constant, depends on the molecular weight which may also be known with reasonable accuracy from the independent experiments on atmospheric composition. From these data, it is believed that the errors in the low altitude densities need be no larger than 15 percent, being introduced jointly by angle of attack effects, instrument errors, and remaining uncertainty in the molecular weight. It is noteworthy that the upper atmospheric density can be defined with better accuracy by the accelerometer measurements than the lower atmosphere density can by direct measurement of temperature and pressure.

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*One way of avoiding the errors associated with low velocities is to design the vehicle to impact the surface at a velocity ratio of 0.2 or greater. As is well known, this is merely a question of selecting the appropriate value of m/C_DA. However, since in our concept all data should, for maximum reliability and simplicity, be communicated between the end of communication blackout and prior to impact, this alternative cuts into the communication time available and therefore into the quantity of data which can be transmitted, and does not seem advisable. This will be discussed further under vehicle design considerations.

Subsonic measurements of pitot and static pressures can be used also to give the terminal velocity, as in a conventional air speed indicator. This more accurate terminal velocity can be used as an anchor point for the measurements of velocity with the accelerometer.

Errors in altitude are, in a sense, equivalent to errors in density, and can be the controlling factor in the overall description of density as a function of altitude. The improved accuracy of the terminal velocity as determined from pitot and static pressure measurements is therefore essential to the accurate determination of altitude. Errors in the entry angle also affect the accuracy of the altitude, but studies of the guidance and tracking capabilities of existing systems for interplanetary vehicles, as well as the separation maneuver required, for example, in perturbing the trajectory onto a planetary impact course from a bus vehicle, indicate that the entry angle can be known and controlled with a few degrees. When the nominal entry angle is 90°, errors in altitude from this source may be smaller than 1 percent.

As a test of the overall definition of atmospheric density structure that might be achieved, analysis has been made including all of the above factors. Errors were introduced consisting of the 0.1 percent full scale acceleration bias, mentioned above, atmospheric temperature errors of 20°F, static pressure errors of 0.4 millibar, and entry angle error of 4°. The density profiles calculated are represented by the symbols in figure 3 and are compared with the "exact" atmospheres postulated. The definition is excellent from ground level to the altitudes where the vehicle is first able to sense the atmosphere, which occurs at density levels of 10^{-5} of Earth sea level density.

<u>Atmospheric Composition Experiments</u>.- In-flight determination of the atmospheric composition would at first seem very difficult to accomplish. The time available for measurement and transmission is short, in general less than a minute. The contamination of any samples taken on board for analysis is difficult to avoid because of the vapor emission from the ablating heat shield, both during the period of intensive heating and afterwards, since the hot shield would be expected to outgas for a period after heating. However, as pointed out in reference 1, there is a naturally-occuring phenomenon of entry which can provide analytical data and which lends itself to very quick response, in the millisecond range if need be. This is the radiative emission from the gases in the shock layer. It is fundamental to gaseous radiation that its spectrum consists of bands, lines, and continua which are characteristic of the gases involved. Measurement of the intensities of selected bands as functions of velocity and free stream density during entry can therefore provide data on the presence or absence of selected constituent gases.

In this experiment also, one must be concerned with contaminating effects of the heat shield vapors, which can emit light when heated in the boundary layer (ref. 4). However, detailed study of both the effects of shield material and the band wavelengths of greatest interest for the atmospheric analysis has indicated that, by selection of materials and wavelengths, the experiment can be conducted on essentially a no-interference basis.

The primary candidate experiment of this kind for the Mars atmospheric probe is the measurement of the presence of nitrogen (as yet only <u>assumed</u> to be a principal constituent of the Mars atmosphere) and its mole fraction. This can be accomplished by measuring the intensity history of the prominent cyanogen violet band system. These bands are responsible for the very high levels of luminous intensity now well known to be associated with nitrogen and carbon dioxide mixtures (refs. 3 and 5). Figure 4 shows a theoretical equilibrium spectrum of a nitrogen, carbon dioxide mixture at a speed and ambient density taken from one of the assumed trajectories of a probe entering Mars. Note that four scale maximums differing by orders of magnitude have been chosen in this presentation, and that the CN violet system is by far the most prominent radiating system. These data were computed by Victor Reis and Henry Woodward of Ames Research Center. The inset oscilloscope trace shows as a function of wavelength the experimental intensity of one of the CN violet side bands, with band head at 4200 Angstroms. The agreement with theory is excellent in detail. This remarkable oscillogram was obtained by Ellis Whiting of ARC.

The experimental variation based on the data of reference 3, of the CN violet band intensity with mole fraction of CO_2 in nitrogen, carbon dioxide mixtures is shown in figure 5 and compared with the theoretical mole fraction of CN behind the shock wave. The comparison is substantially 1/1. Given the free stream conditions, then, and a gaseous atmosphere consisting primarily of nitrogen and carbon dioxide, the measurement of CN violet intensity can be used to define the proportions of N_2 and CO_2, except for an ambiguity that arises because the curve is double valued. However, for any given pair of gas mixtures, this ambiguity occurs at one velocity only. Thus, figure 6 shows that 9 percent and 25 percent CO_2 mixtures cannot be distinguished at 19,000 feet per second, but at all other speeds, they can be. Thus, from radiometric measurements of the intensity of the CN violet system as a function of time during entry, the presence of nitrogen can be determined, and its mole fraction established.

Additional radiometers sensing the NO gamma bands, the C_2 Swan bands, and the $N_2^+(1-)$ provide additional checks on the interpretation of the CN violet radiometer. Thus, if the readings of these instruments are not consistent with those expected from CO_2 - N_2 mixtures, it is implied that other gaseous constituents are present in important amounts. For example, the presence of nitrogen oxides in the atmosphere would enhance the NO system. Argon increases the shock layer temperature at a given speed, and shifts the peak intensity of the CN system to a lower velocity (ref. 6). The interpretation of these readings would be assisted both before and after the flight experiment by use of laboratory experiments with ballistic ranges and shock tubes. These facilities are currently being used to study non-equilibrium aspects of the shock layer radiation for this kind of experiment.

The presence of trace amounts of water vapor may lead to some measurable response in the spectrum. Since this is of great interest biologically, it is receiving current laboratory attention at ARC.

<u>Vehicle Design Considerations</u>.- Given this set of experiments to be performed, what is the description of the vehicle best suited to carry them out? To perform the shock layer spectroscopic experiment, the vehicle must be blunt, and must have the means for measuring angle of attack. To communicate the data acquired during entry after blackout and before impact, the vehicle must be of low m/C_DA, or equivalently, of low density. The effect of m/C_DA on communication time is shown in figure 7 for one of the lowest density atmospheres considered, one with 11 millibars surface pressure and a scale height of 22,20[redacted]t. Communication is assumed to begin when the velocity drops below 10,000 ft/sec. To maintain communication time of 20 seconds or longer requires that m/C_DA be 0.25 slug/ft^2 or less. This has been selected as a nominal target value for m/C_DA. With atmospheres of higher surface pressure, the communication time is increased as shown.

Estimates by Mr. Dale Lumb of ARC, and others, have indicated that communication bit rates in the order of 300 bits per second might be obtained by relay link to a fly by bus or orbiting vehicle at a range of 30,000 km or less. In 20 seconds, this permits a total of 6000 bits of data to be communicated, an amply large number for these experiments. Minimum bit estimates have indicated that the main data would require less than 2000 bits. On the other hand, direct communication to Earth is clearly inadequate for these experiments, if it is limited to 3 or 4 bits per second.

Next consider the configuration of the blunt, low density vehicle to be employed. From study of an atmospheric density structure experiment to be performed with a single axis accelerometer, Victor Peterson of ARC reasoned from the trajectory equations of motion that it was desirable to select a configuration having small variation in the ratio of drag coefficient to axial force coefficient with angle of attack, and small lift curve slope. This led him to select the sphere as a most suitable shape. Further study has shown additional reasons why this selection appears correct. The basic advantage is that the drag force is independent of attitude and is the only steady aerodynamic force on a sphere. For any other configuration, the drag acceleration of a body oscillating in pitch fluctuates with frequency equal to the pitching frequency, and digital sampling of the acceleration at arbitrary intervals, say 0.5 second, would fail to properly define the acceleration history, particularly in view of the typical pitching frequency of bodies of the size under consideration which is 5 to 10 cycles per second. This kind of error in the acceleration is fully as damaging to the accurate definition of velocity (eq. 2) and density as error in the accelerometer itself, which, we have shown, must be very small. Hence, the use of bodies which have fluctuating components of pathwise acceleration requires data sampling at intervals frequent enough to define the oscillating acceleration, say 5 samples per cycle at 5 cycles per second, or 25 readings per second. By comparison, the sphere does very well on 2 readings per second. It is therefore apparent that the total data to be communicated is minimized by the sphere, or, for the same amount of data, it can perform the atmosphere structure experiments with vastly improved accuracy compared to other shaped bodies.

Other advantages of the sphere may be cited. The definition of angle of attack is simplified (fig. 8). As may be seen, the ratio of the normal accelerometer reading to the axial accelerometer reading gives the tangent of the angle of attack in that plane. With other configurations, the presence of the lift force requires that wind tunnel data enter into the interpretation of the accelerometer readings to obtain angle of attack, and there is a consequent loss of precision. In addition, the drag coefficient of spheres is perhaps more extensively documented than that of any other bodies. It should be known within a few percent at the high speed conditions where deceleration measurements will be employed to define the density, and should not be sensitive to gas composition at hypersonic speeds (ref. 2). Furthermore, the changes in body profile brought about by ablation are so small that errors in drag coefficient from this source may be neglected.

It should be mentioned that in this application the sphere has its center of mass ahead of the geometric center to aerodynamically stabilize it about the desired flight orientation. The equation of the static stability coefficient is included in figure 8.

Thus, we conclude that the sphere is the preferred shape for the Mars atmospheric probe. This, however, does not imply that the sphere will also be optimum for payload landing vehicles. We are, in fact, quite sure it is not, since preference in those cases goes to vehicles which maximize the product of drag coefficient and ratio of frontal area to surface area. This assures that the Apollo configuration, among others, will be superior to the sphere for soft-landing payload. This latter problem has been discussed in a recent article in this Journal (ref. 7).

To further specify the design and feasibility of a spherical Mars atmospheric probe, we and our associates at Ames Research Center have made estimates of the weight and size requirements of the instrumentation and its associated electronics and communication equipment, and have considered the problem of designing a light enough structure and heat shield. We conclude that the instruments can easily be housed in a sphere of 1-foot radius, which, for the given m/C_DA, would have a total weight at Earth of 23.[illegible] pounds. The payload weight is estimated at less than 15 pounds. Work by Robert Clapper and Fred Matting has indicated that the structure and heat shield might, in this size, be built for as little as the 9 pounds available. However, if meeting the gross weight proves impossible at this radius, one can readily consider a larger radius, say 1.25 feet, at which the gross weight for the given m/C_DA becomes 37 pounds, while the payload weight remains fixed at 15 pounds, so that 22 pounds are available for structure and heat shield. These weights are clearly adequate.

A conceptual sketch of the vehicle and its payload is presented in figure 9.

Summing Up.- The necessity for having more definite information on the Mars atmosphere is very great, not only for the long range manned missions, but also for the more immediate unmanned landing missions to perform biological and physical measurements. The penalty for proceeding with these latter missions without better atmospheric data is in reduced payload and reduced probability of success.

Logically, the definition of the atmospheric properties should be the goal of the first entry mission. This can be accomplished without soft landing, thereby enhancing the chances of success, and can also be done in a small and simple enough device that thermal sterilization of the entire vehicle as a unit seems reasonable, not only from the standpoint of obtaining sterility, but also from the standpoint of engineering design.

The experiments on atmospheric structure should lead to data on the density and pressure profiles of the Mars atmosphere accurate within 15 percent at the worst point, from ground level to the altitude where the accelerometer first senses the atmosphere (well above 200,000 feet, depending on the atmosphere). Direct measurement of the atmospheric temperature at low altitude also seems attainable.

The experiment on composition will determine directly whether or not nitrogen is present as a principal constituent gas, and in what proportions. Search for important quantities of nitrogen oxides and argon is also possible. An as yet undemonstrated possibility which may materialize is the analysis for trace amounts of water vapor.

Such an experiment seems well suited as a forerunner to the larger and more complicated vehicles to follow.

References

1. Seiff, A., "Some Possibilities for Determining the Characteristics of the Atmosphere of Mars and Venus From Gas-Dynamic Behavior of a Probe Vehicle." NASA TN D-1770, April 1963.

2. Seiff, A., "Atmosphere Entry Problems of Manned Interplanetary Flight." Paper presented at AIAA Conference on Engineering Problems of Manned Interplanetary Exploration, Palo Alto, California, September 30 - October 1, 1963.

3. James, C. S., "Experimental Study of Radiative Transport From Hot Gases Simulating in Composition the Atmospheres of Mars and Venus." Paper presented at AIAA/MIT Conference on Physics of Entry Into Planetary Atmospheres, August 1963, AIAA Paper 63-455.

4. Craig, R. A. and Davy, W. C., "Thermal Radiation From Ablation Products Injected Into a Hypersonic Shock Layer." NASA TN D-1978, 1963.

5. Thomas, G. M. and Menard, W. A., "Experimental Measurements of Nonequilibrium and Equilibrium Radiation From Planetary Atmospheres." Paper given at AIAA Entry Technology Conference, Williamsburg, Virginia, October 12-14, 1964.

6. Wolf, F. and Horton, T., "Effect of Argon Addition on Shock-Layer Radiance of CO_2 - N_2 Gas Mixtures, AIAA Journal, August 1964, p. 1472.

7. Roberts, L., "Entry Into Planetary Atmospheres," Astronautics and Aeronautics, October 1964.

EFFECT OF ATMOSPHERE ON ENTRY TRAVECTORY

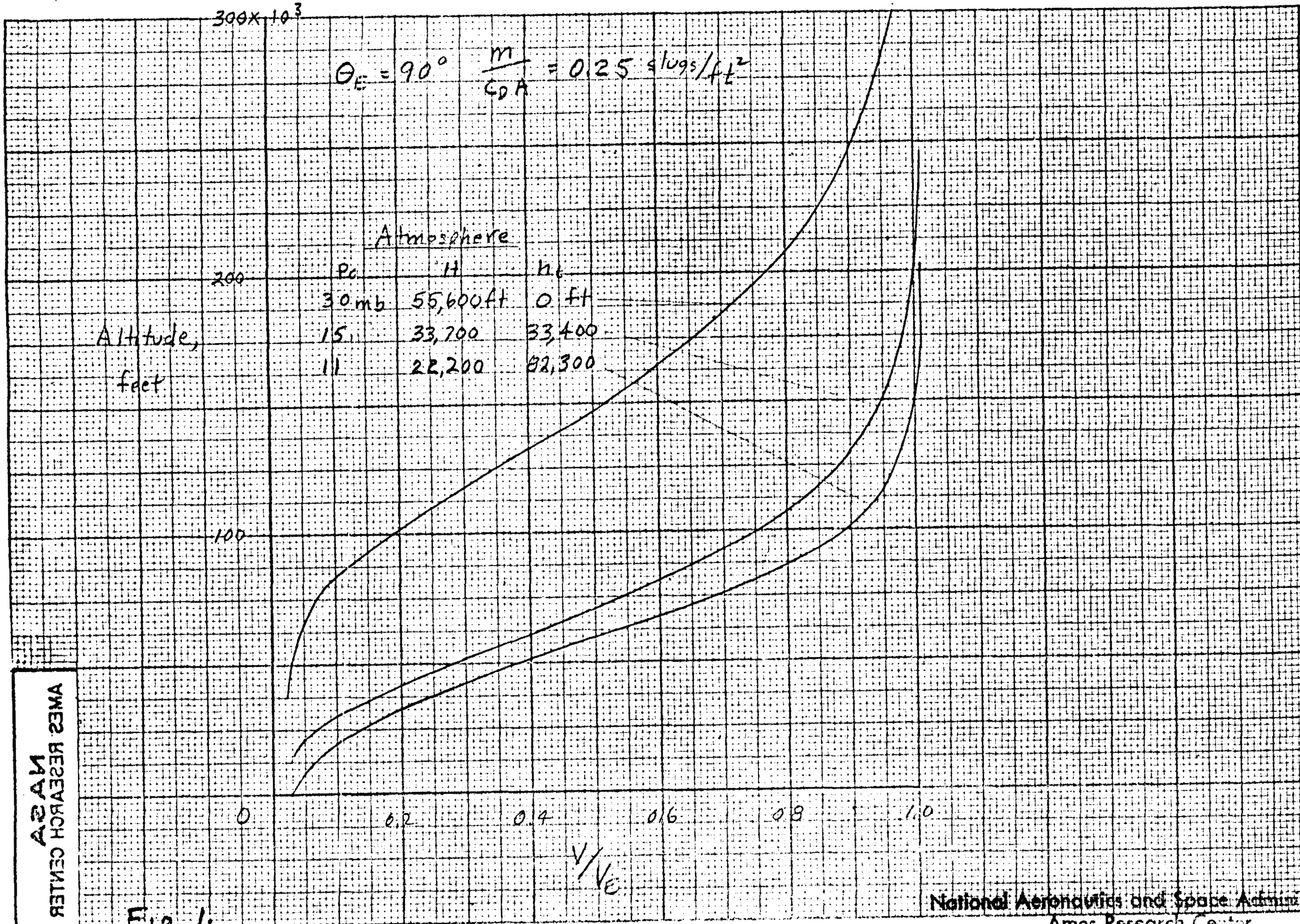

Fig 1.

EFFECT OF ACCELEROMETER ERROR ON DENSITY DETERMINATION

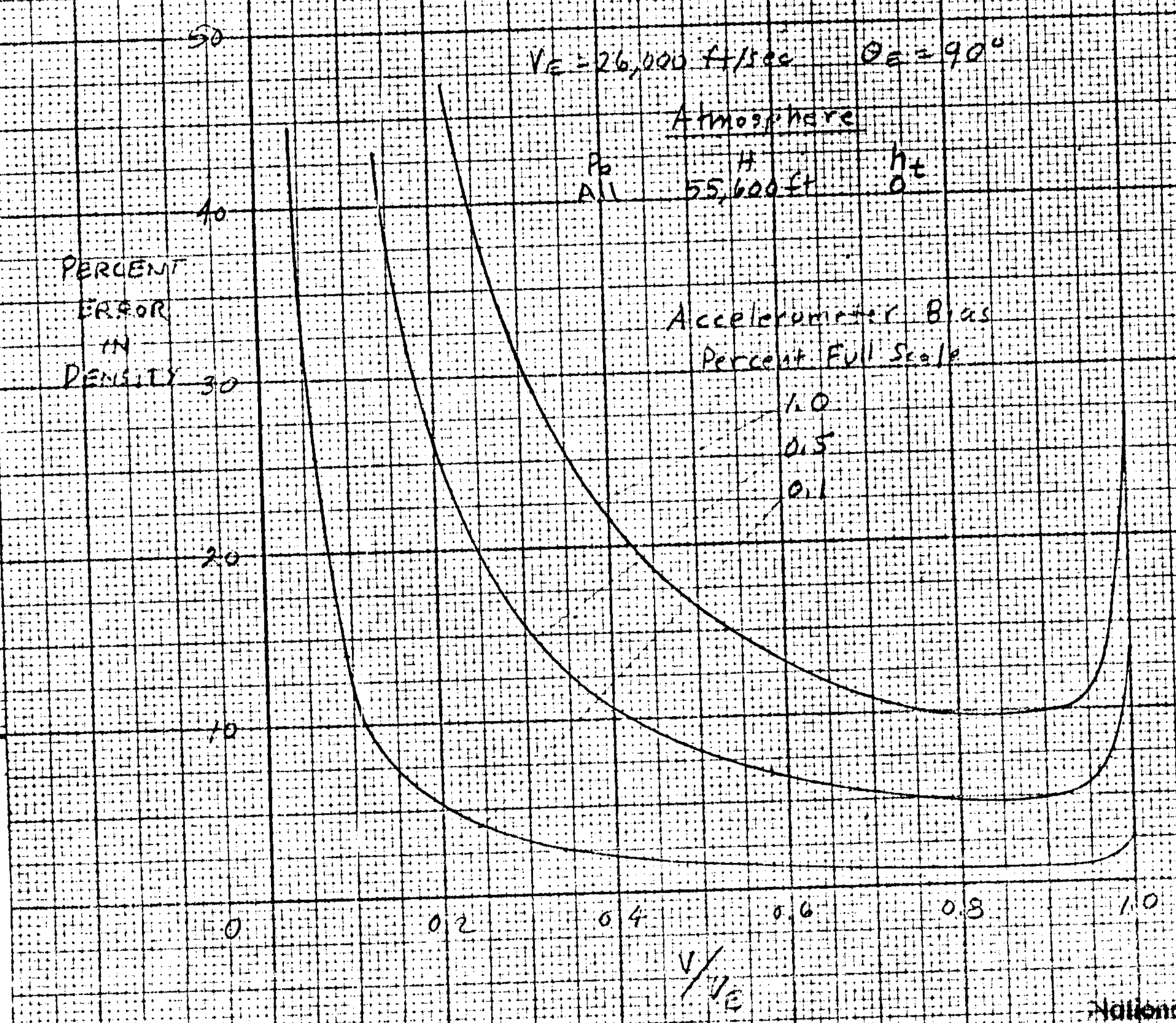

Fig 2

ENTRY ANALYSIS SIMULATION

$V_E = 26{,}000$ ft/sec

$\gamma_E = -90°$

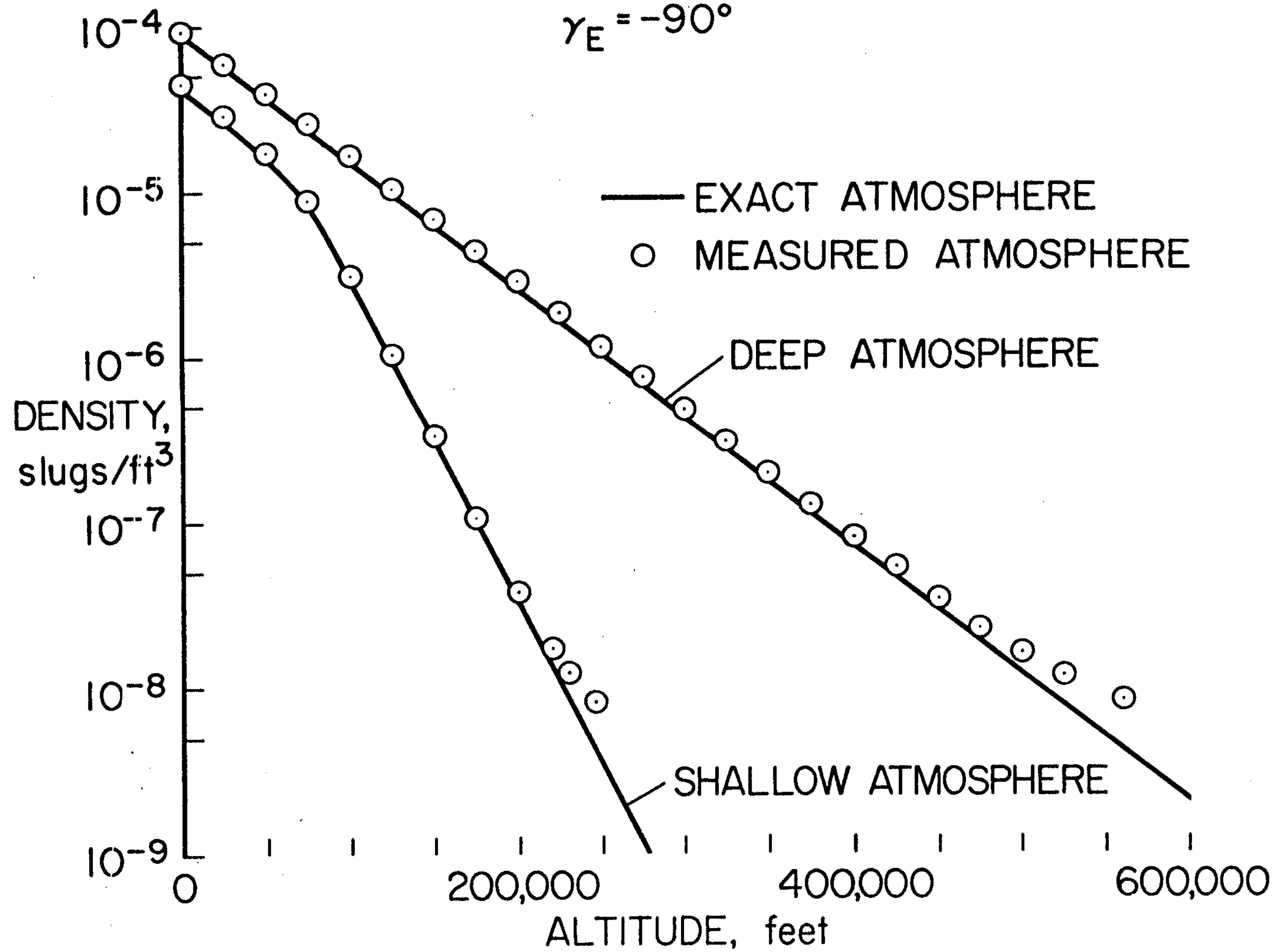

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Fig. 3

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AMES RESEARCH CENTER

CALCULATED SHOCK LAYER SPECTRA FOR
25% CO_2 - 75% N_2 GAS MIXTURE
$V = 6.71$ km/sec $\rho/\rho_{0_\oplus} = 0.001$

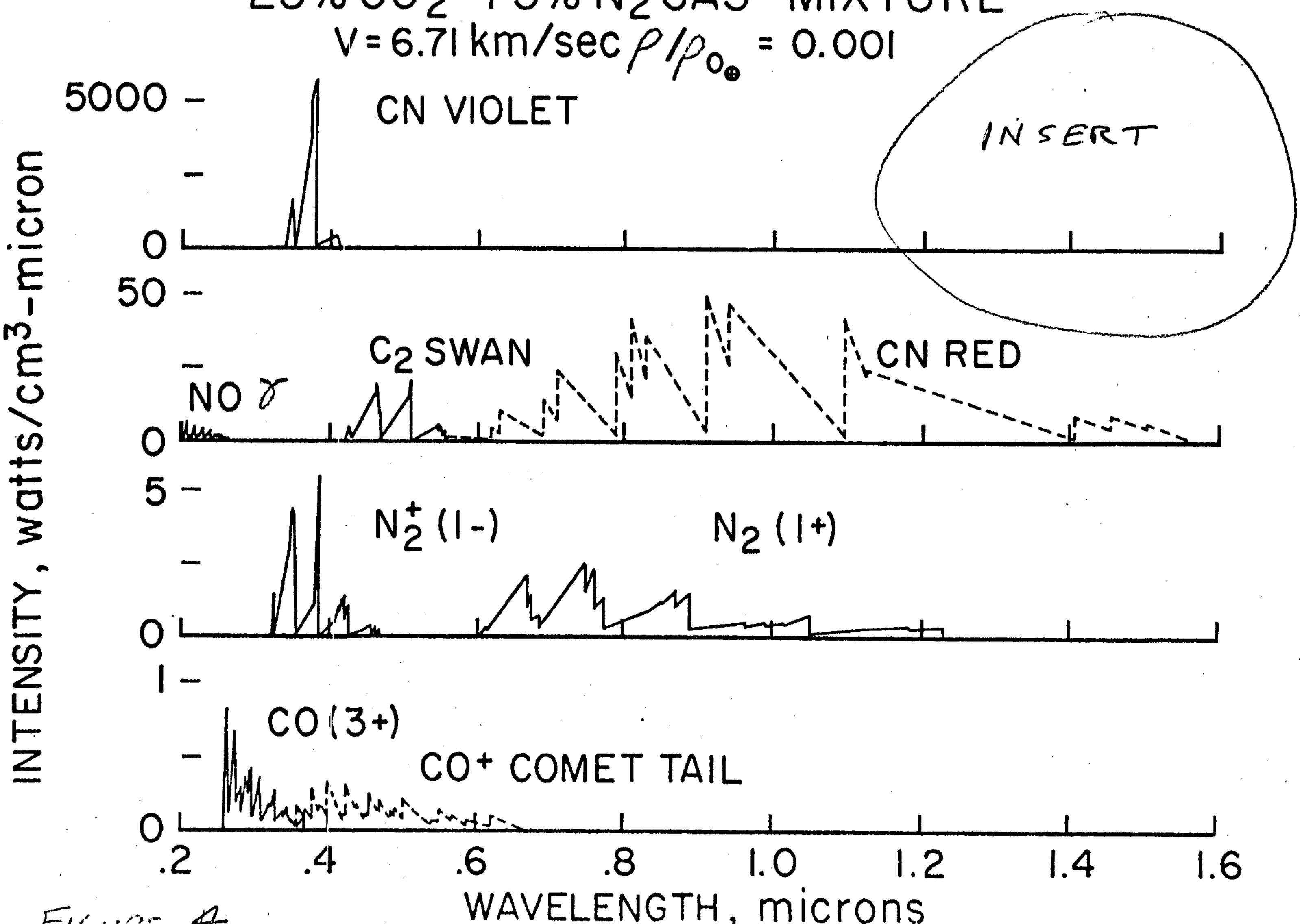
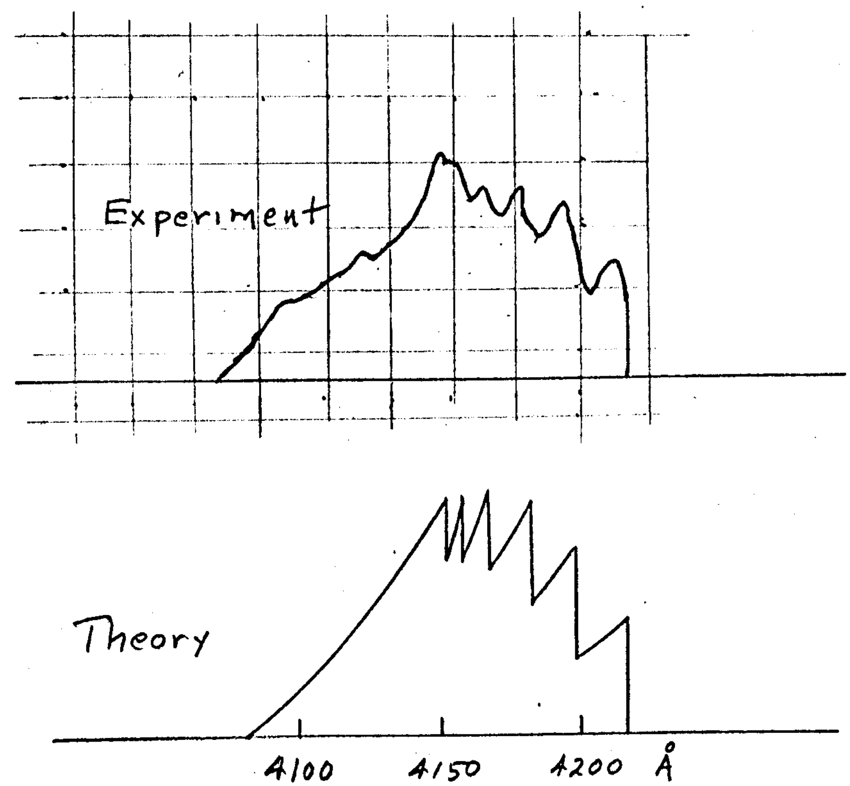


FIGURE 4



Insert for Fig. 4

MIXTURE DEPENDENCE OF CN VIOLET RADIATION

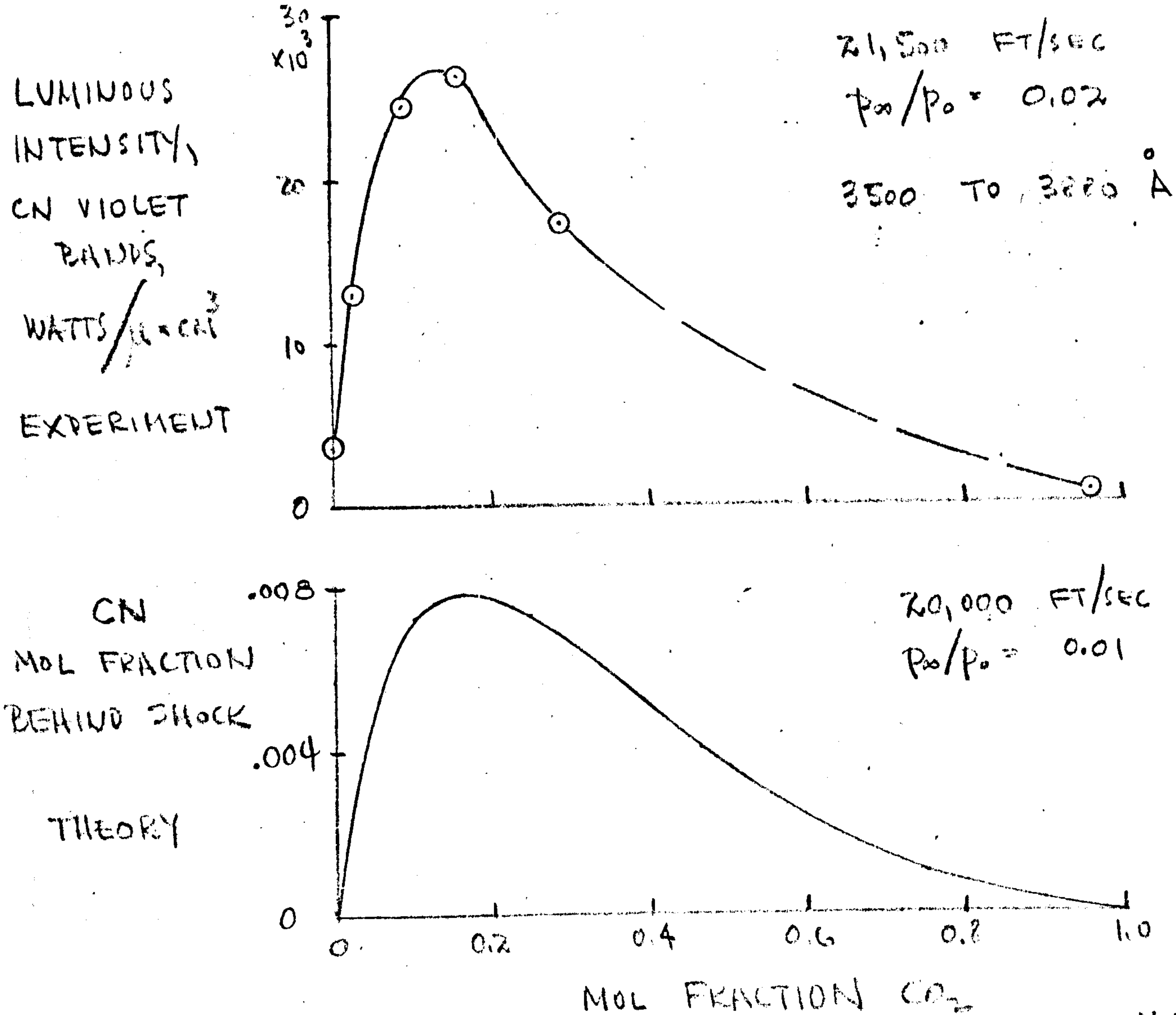


FIGURE 5

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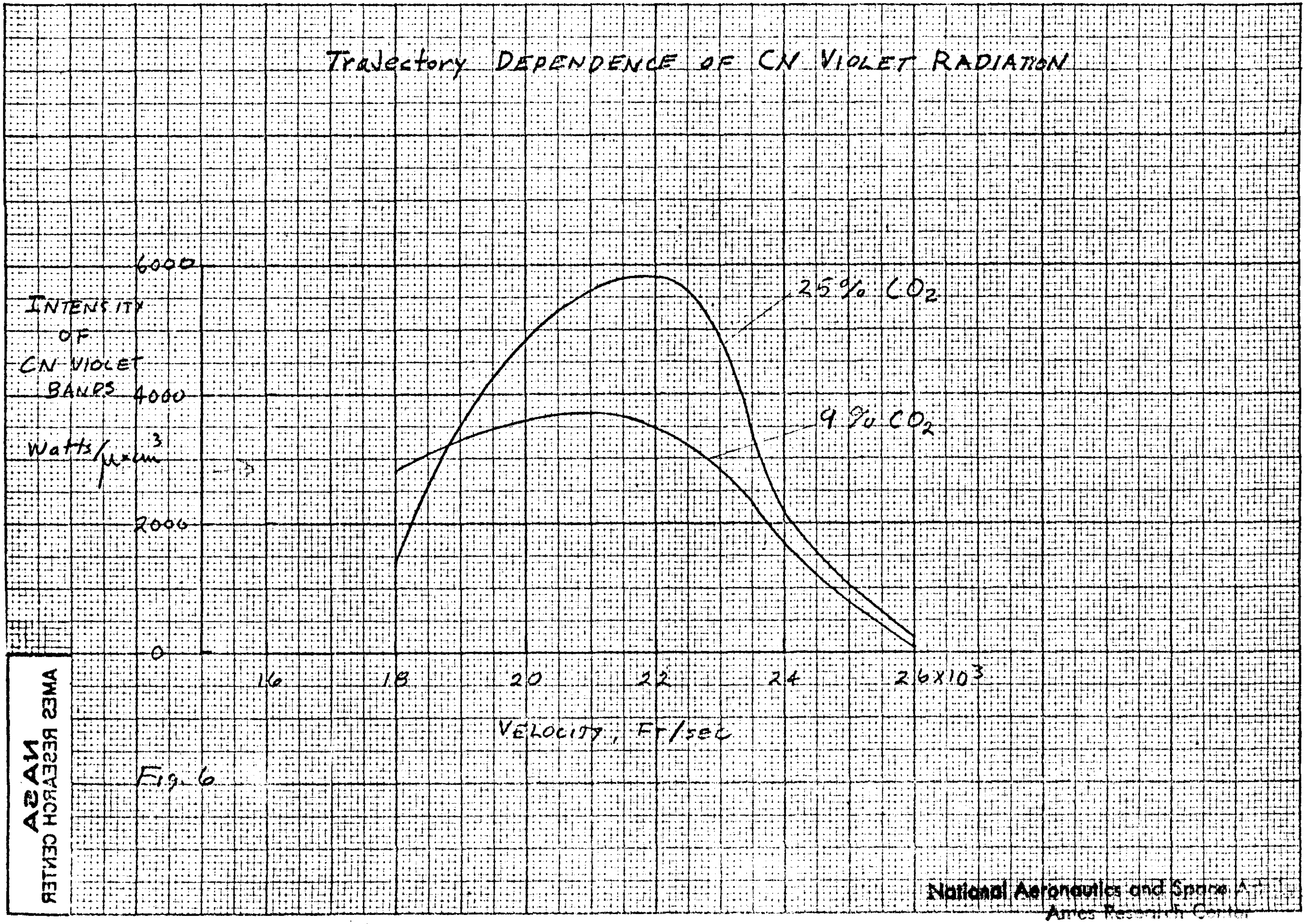

Trajectory DEPENDENCE OF CN VIOLET RADIATION
INTENSITY OF CN VIOLET BANDS Watts/$\mu \times cm^3$
6000
4000
2000
0
16
18
20
22
24
26×10^3
VELOCITY, FT/sec
25% CO_2
9% CO_2
NASA AMES RESEARCH CENTER
National Aeronautics and Space A...
Ames Research Center
Moffett Field, Calif.

Fig. 6

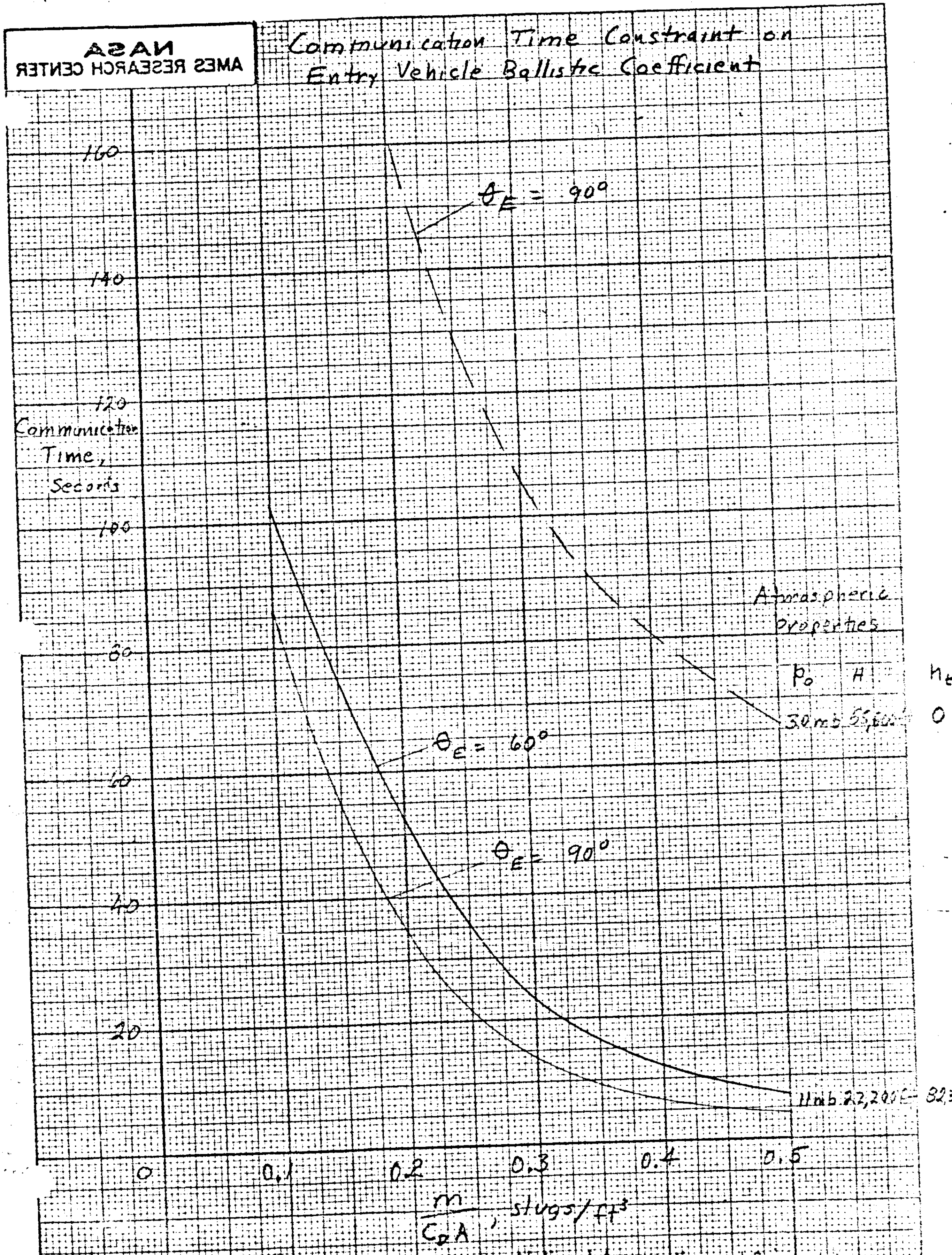
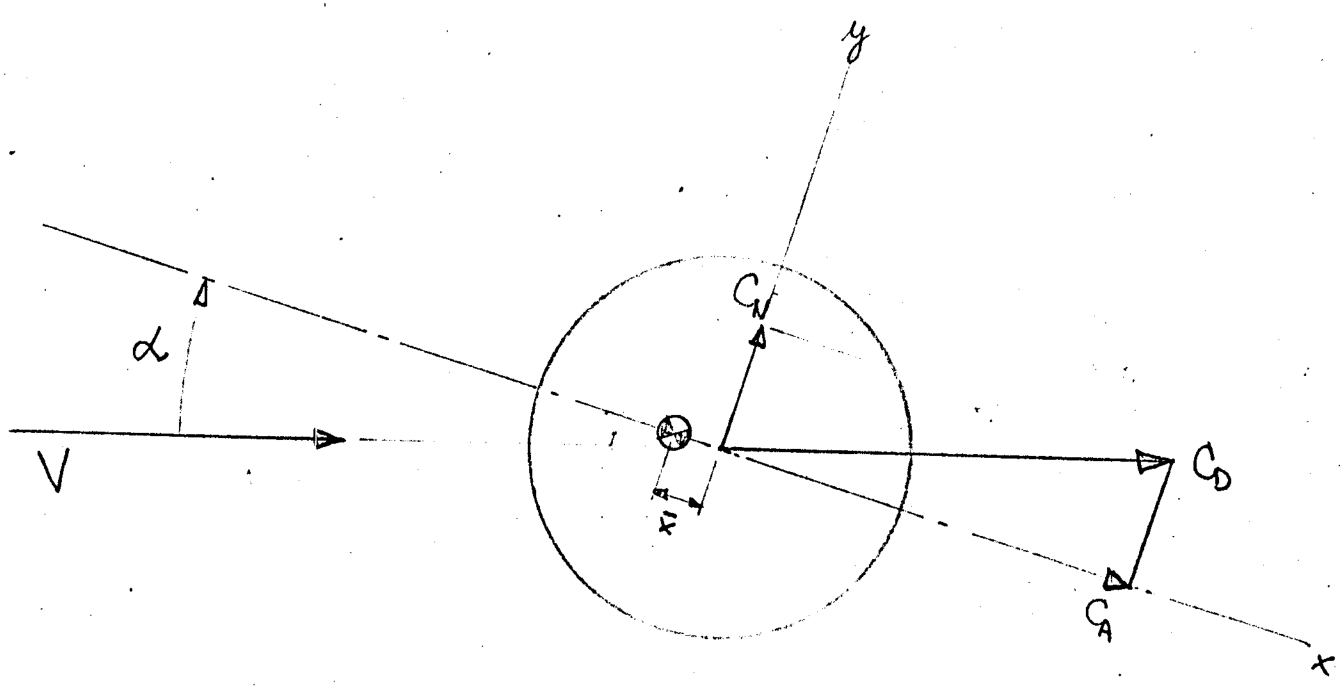

Communication Time Constraint on
Entry Vehicle Ballistic Coefficient
Communication Time, Seconds
$\theta_E = 90^\circ$
$\theta_E = 60^\circ$
$\theta_E = 90^\circ$
Atmospheric properties
p_o H h_E
30mb
11mb 22,200
0
0.1
0.2
0.3
0.4
0.5
20
40
60
80
100
120
140
160
$\frac{m}{C_D A}$, slugs/ft^3

Fig. 7

ANGLE OF ATTACK DEFINITION FOR A SPHERE



$$\tan\alpha = \frac{C_N}{C_A} = \frac{a_y}{a_x}$$

$$C_{m_\alpha} = C_{N_\alpha}\bar{x} = C_D\bar{x}\cos\alpha$$

FIG. 8

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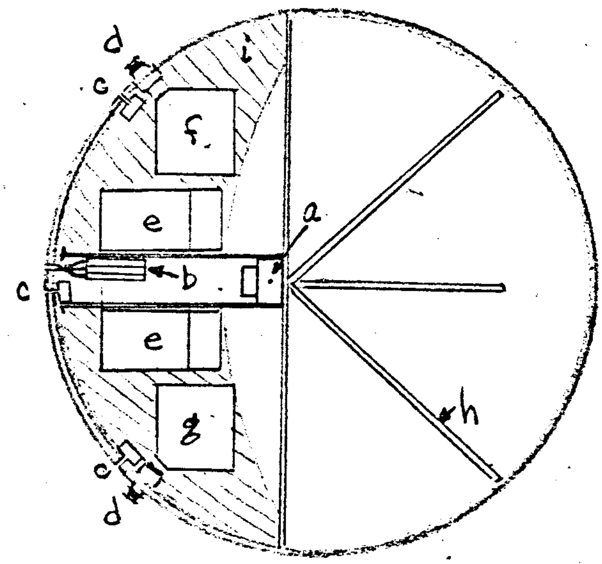
MARS ATMOSPHERE PROBE ARRANGEMENT



a. 3 axis accelerometer, on c.g.

b. 4 channel radiometer

c. pressure sensors

d. static temp. sensors (deployed at low speeds)

e. telemetry transmitter

f. data storage unit

g. batteries and power conditioning

h. transmitting antenna

i. plastic foam

Fig. 9